Space Weather in the Ionosphere and Thermosphere

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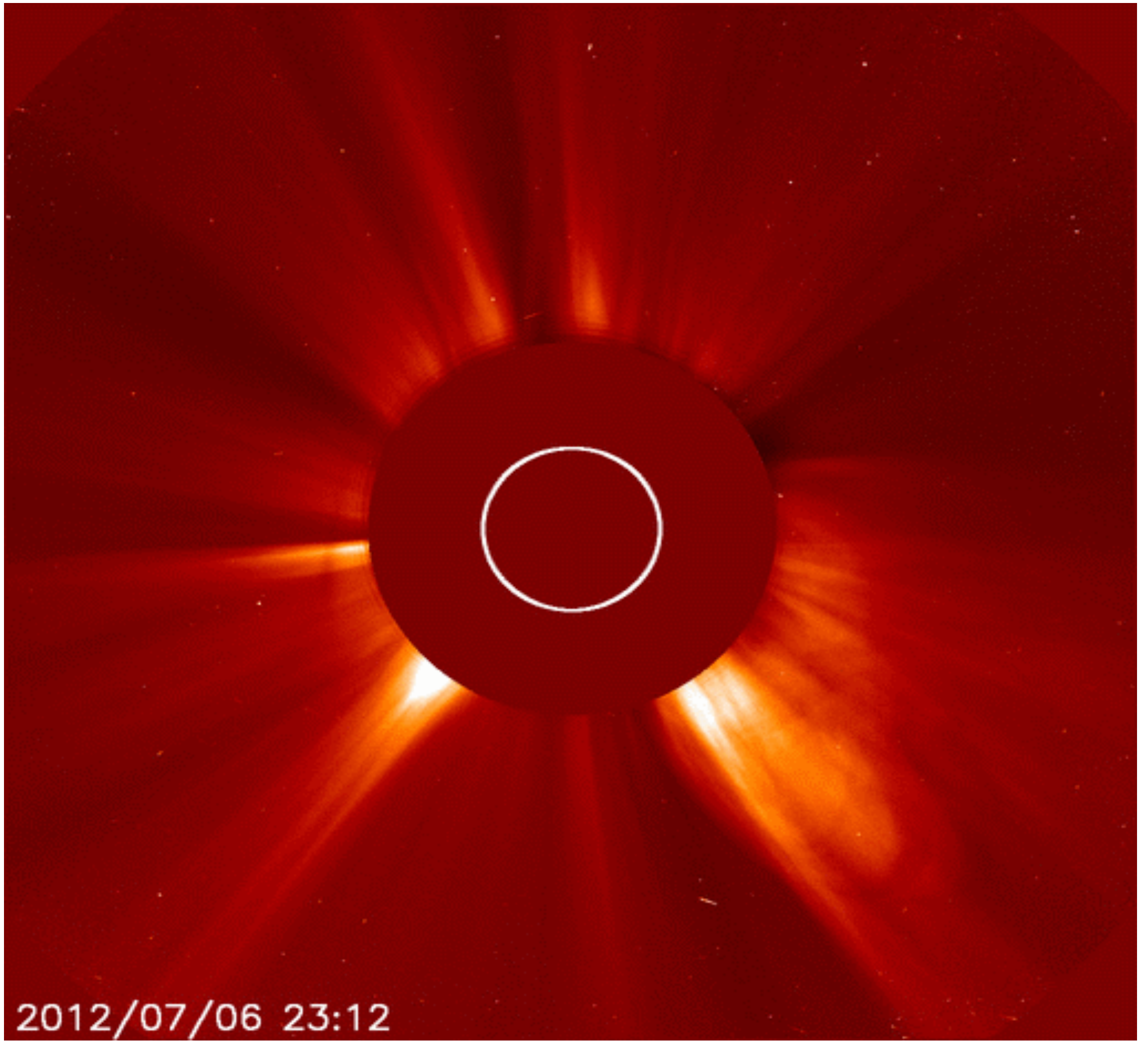
CCMC Space Weather Bootcamp, June 2017

Content

- Introduction to the Ionosphere and Thermosphere
- Space weather Impacts on the Ionosphere and Thermosphere

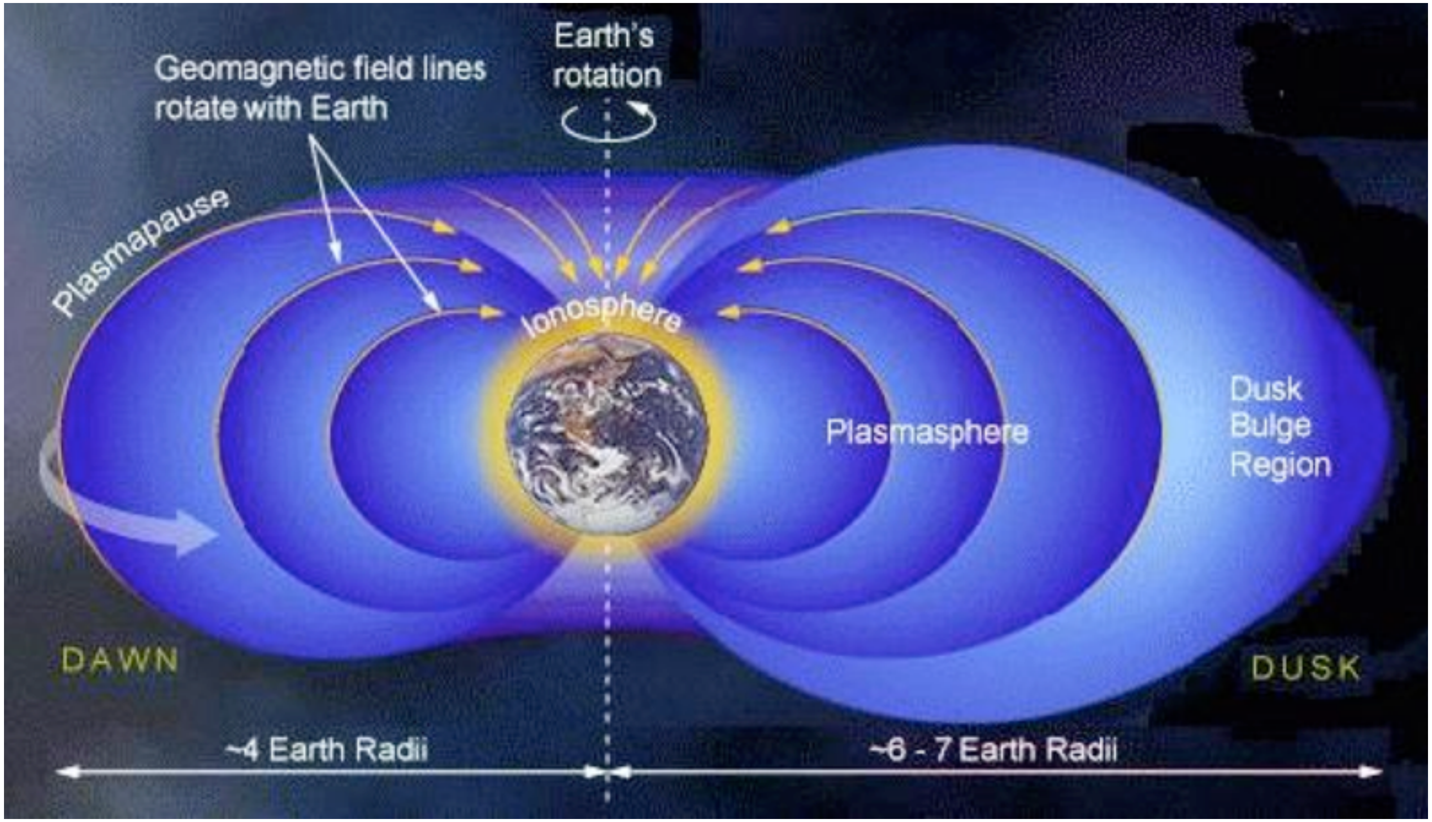
Space Weather



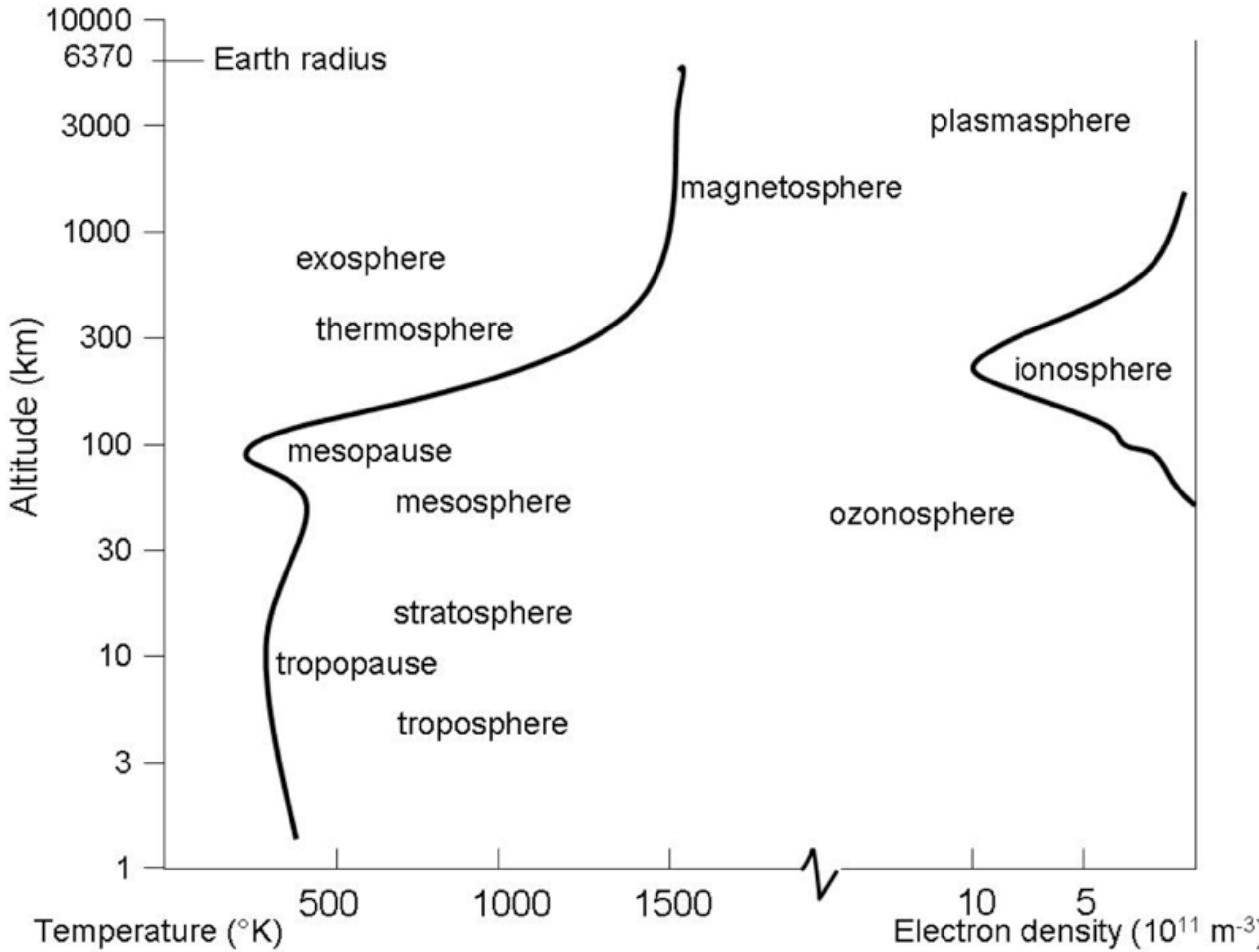
Ionosphere

- The Earth’s environment is comprised of gases that surrounds the planet and are retained by the Earth’s gravity.
- The atmosphere absorbs ultraviolet radiation from the Sun, thereby protecting life on Earth.
- The ionosphere is the densest plasma region in the Earth’s atmosphere generated by ionization from incoming solar radiation.
- The ionosphere contains some of the most complex chemical processes in the atmosphere, which makes for interesting, useful and exciting science.

Near-Earth space environment



Regions of atmosphere in terms of temperature and density

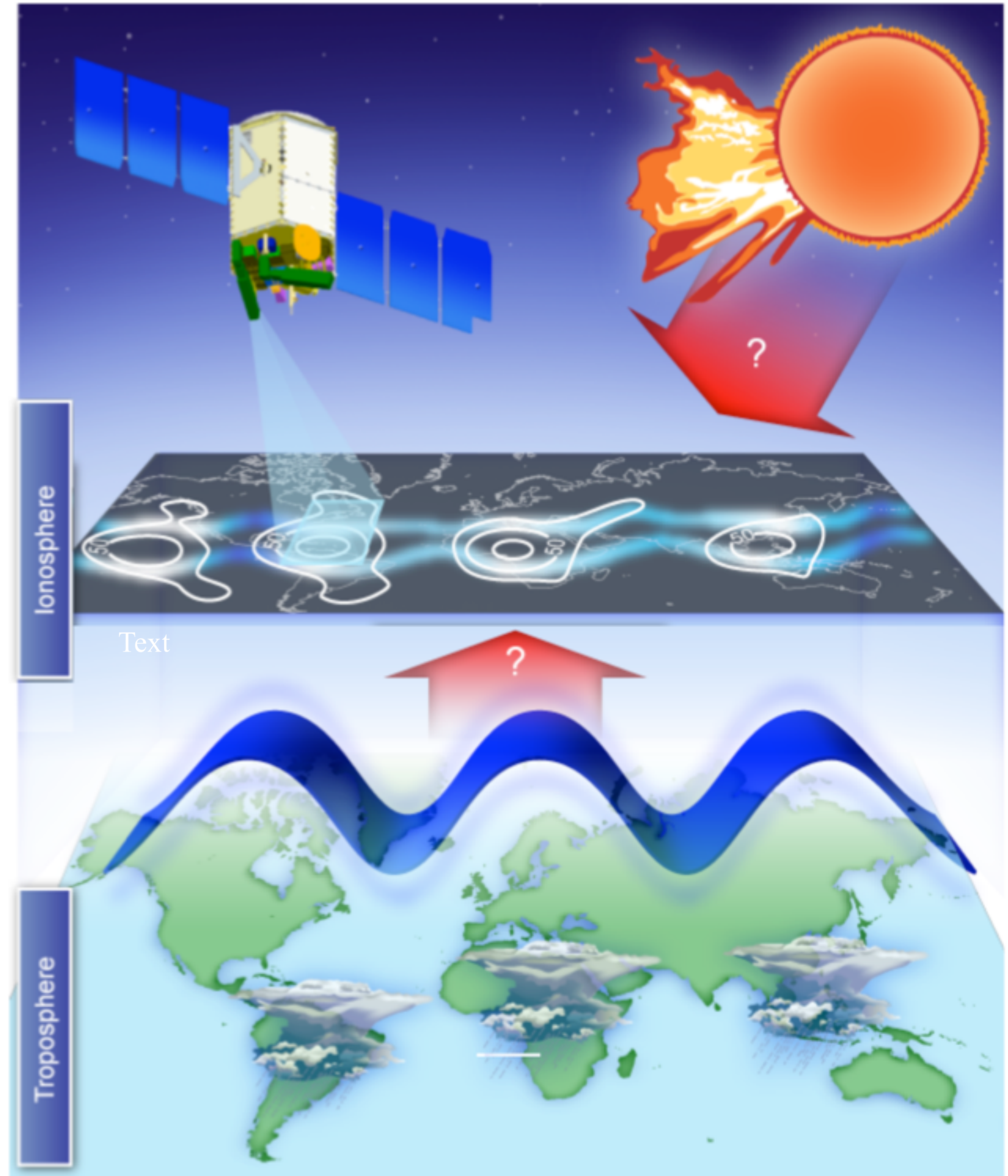


Courtesy of Lee-Anne McKinnell

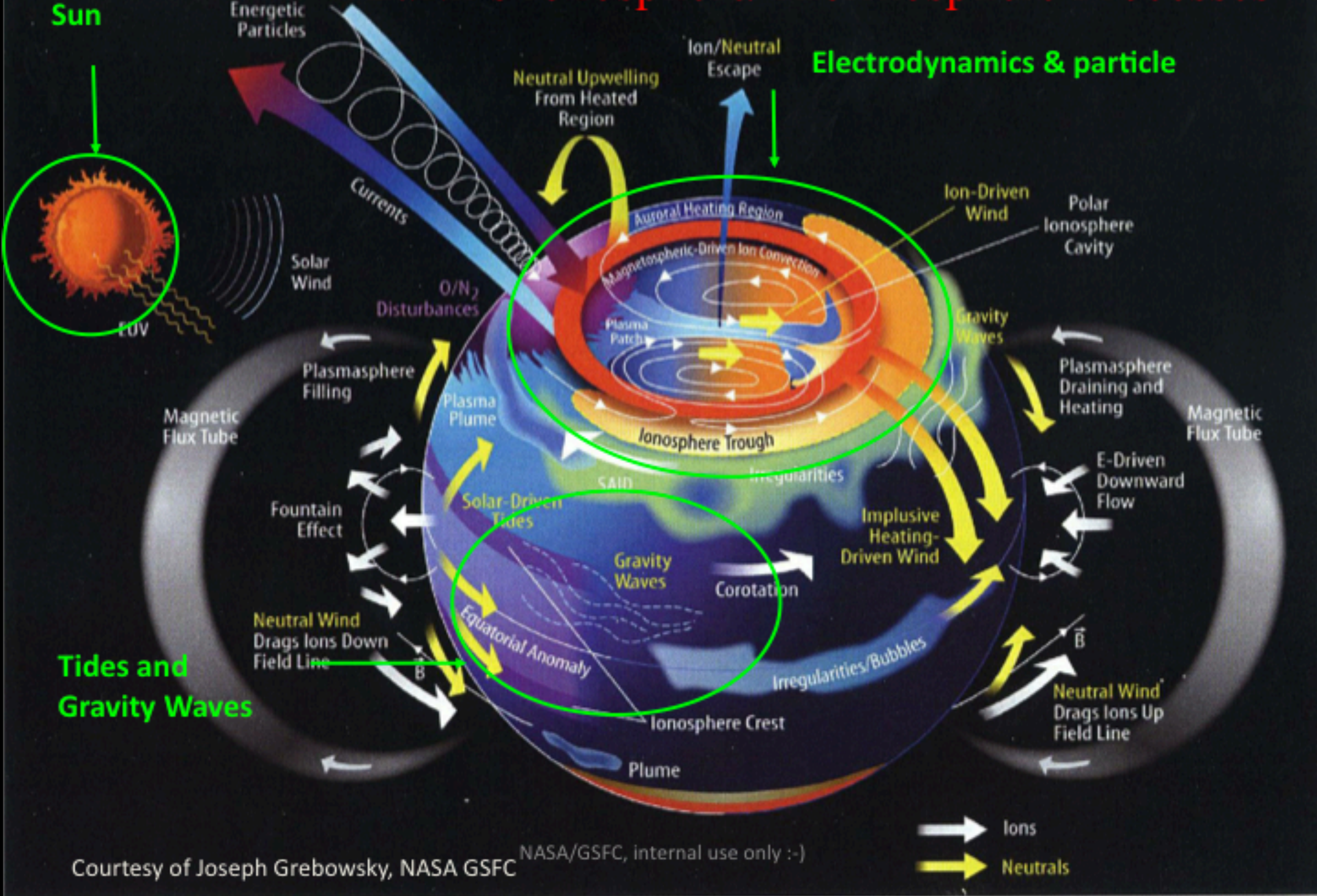
The ionosphere is traditionally believed to be mainly influenced by forcing from **above** (solar radiation, solar wind/magnetosphere)

Recent scientific results show that the ionosphere is strongly influenced by forces acting from **below**.

Research remains to be done:
How competing influences from above and below shape our space environment.



Earth's Ionosphere/Thermosphere Processes



Courtesy of Joseph Grebowsky, NASA GSFC

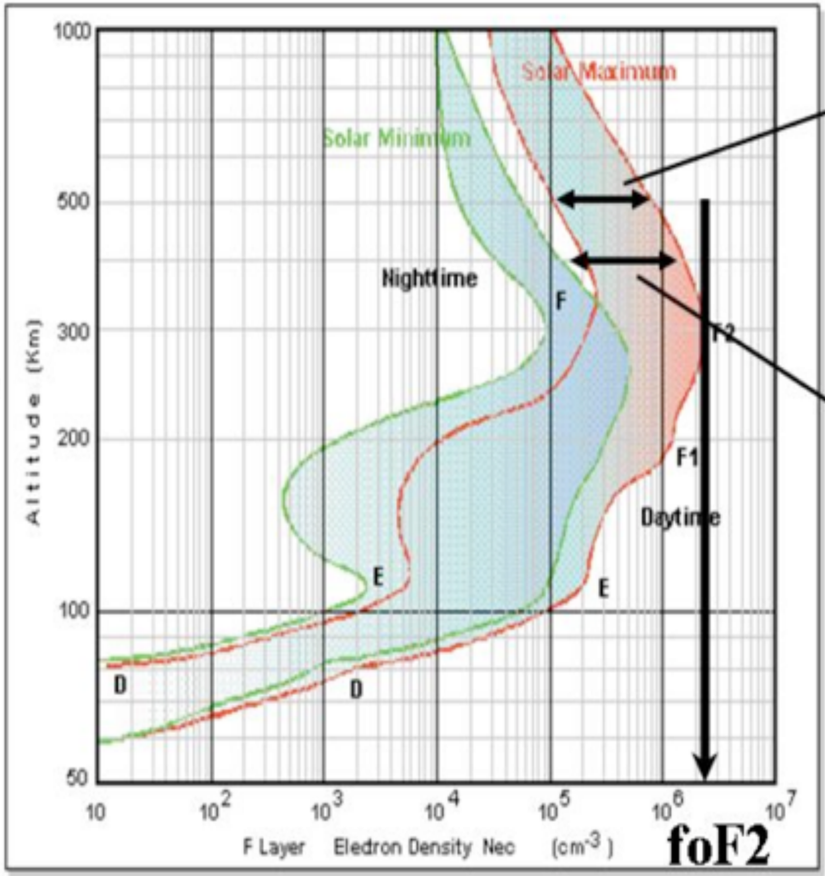
The ionosphere is variable

(highly non-linear and changing medium)

Seasonal variation
(1yr)

Magnetic activity
variation

Latitude
dependence



Diurnal variation
(24 hrs)

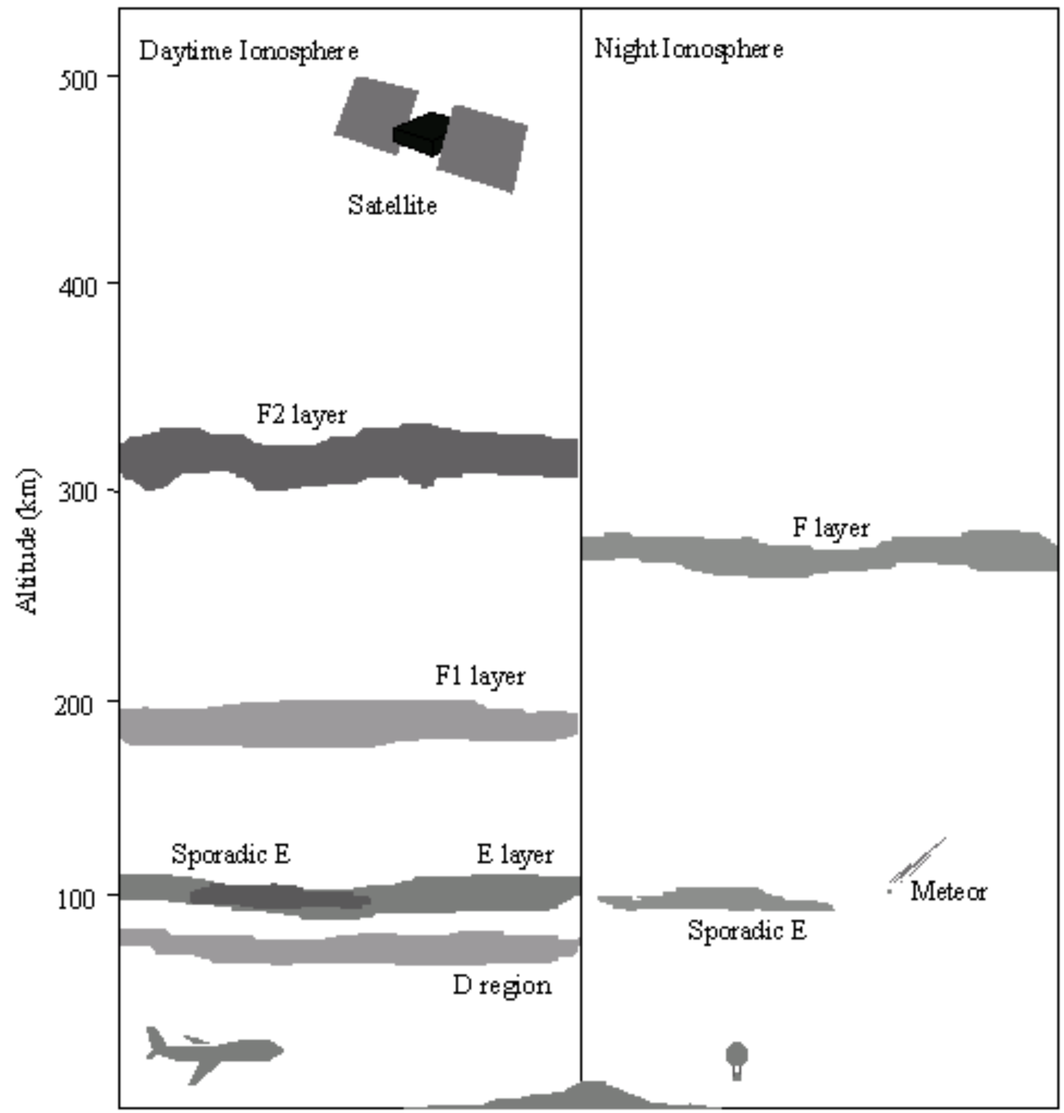
Solar activity
variation
(22 yrs)

Day/night ionospheric structure

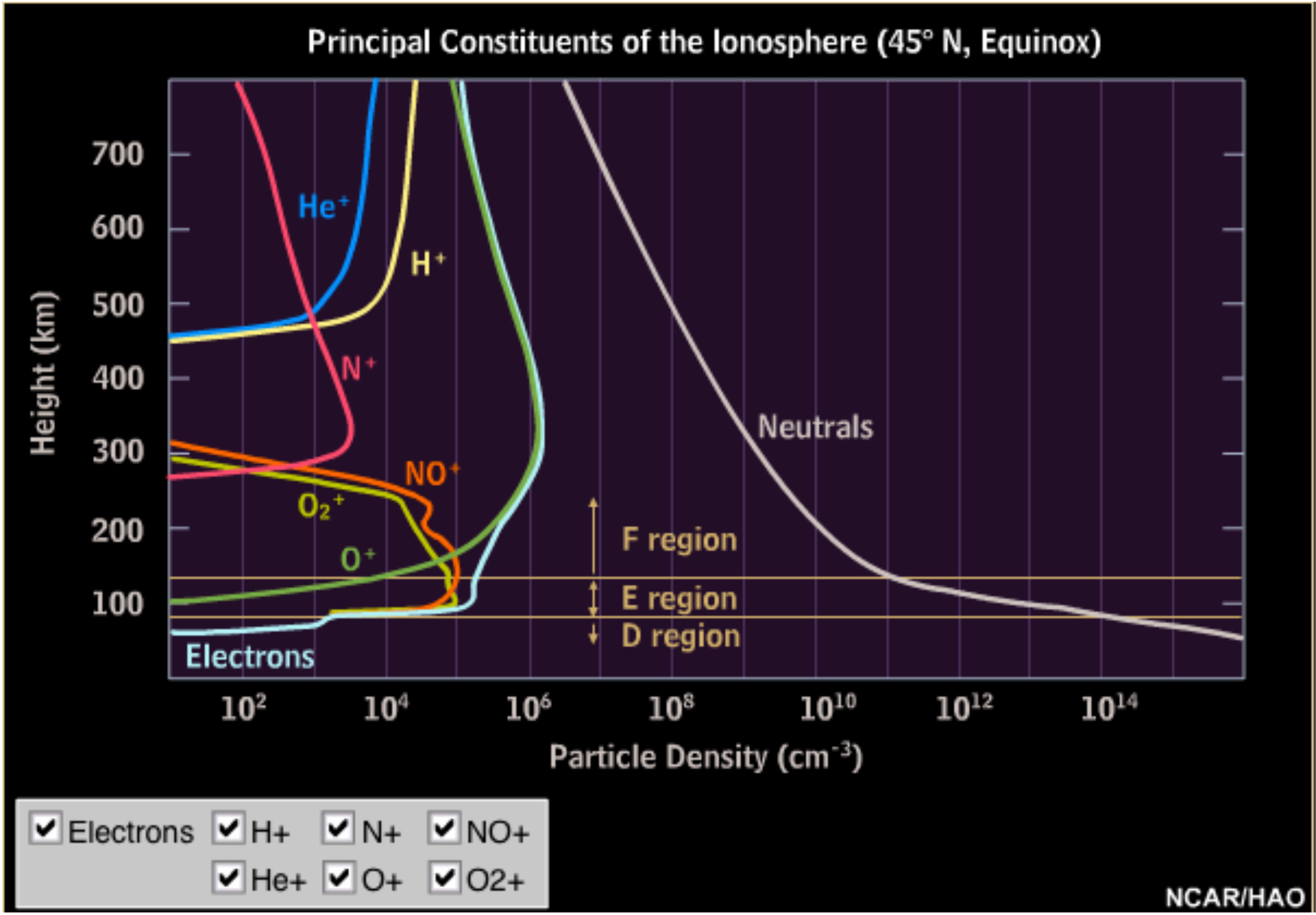
-Ionosphere is formed by solar EUV/UV radiation.

- Day/night ionosphere is very different

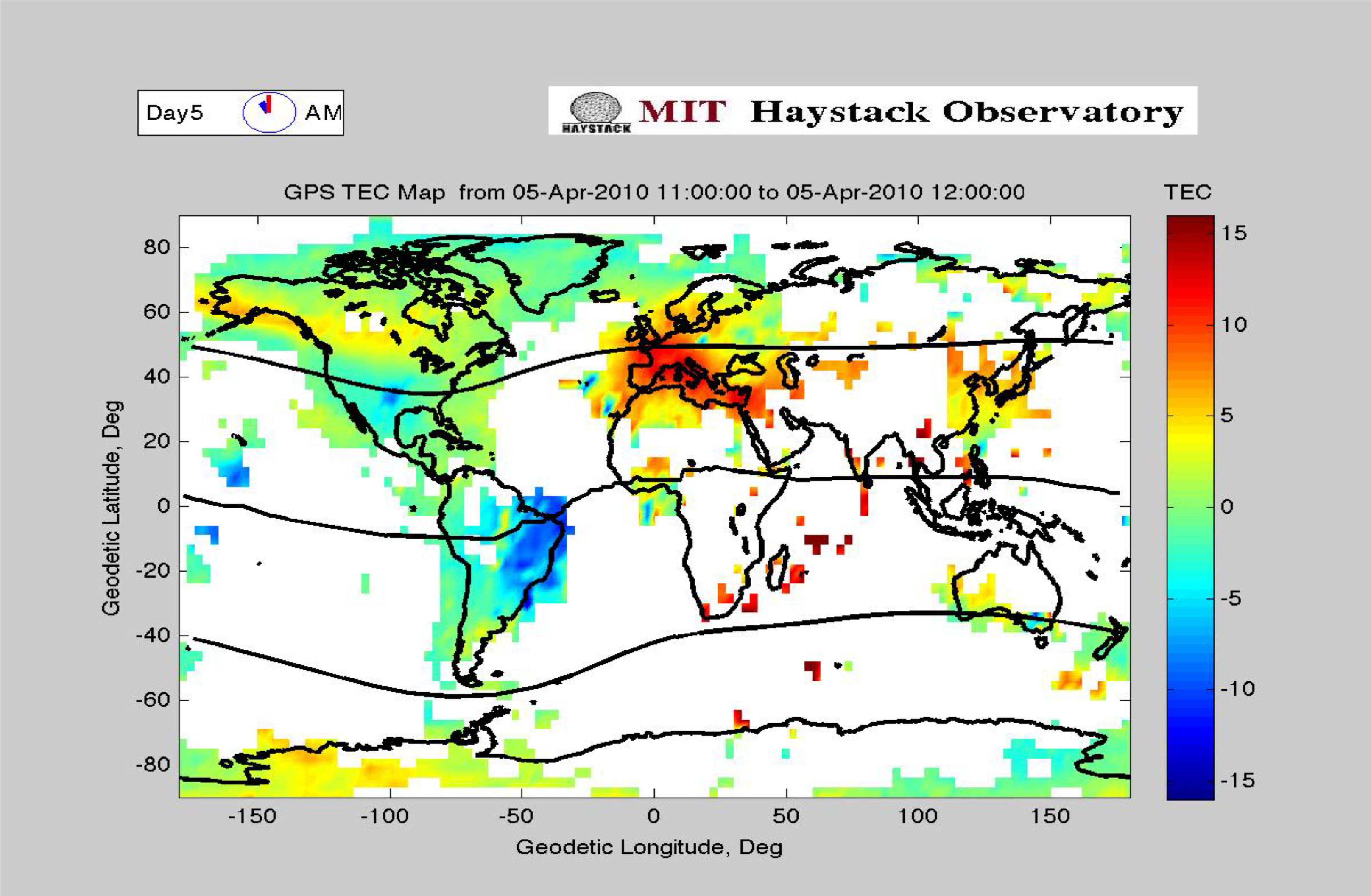
D region 50 to 90 km;
E region 90 to 140 km;
F1 region 140 to 210 km;
F2 region over 210 km.



Composition of ionosphere



Global ionospheric density distribution



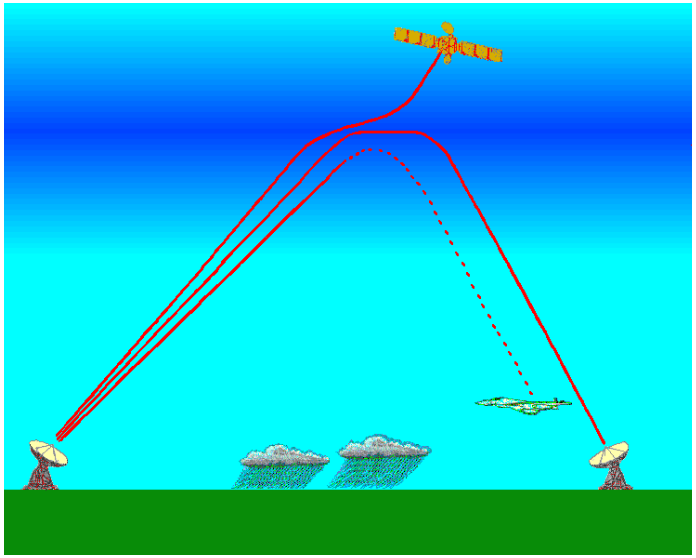
Ngwira et al., (AGU Monograph 220, 2017)

Ionospheric electromagnetic wave propagation

Reflects, refracts, diffracts & scatters radio waves, depending on frequency, density, and gradients

Plasma frequency

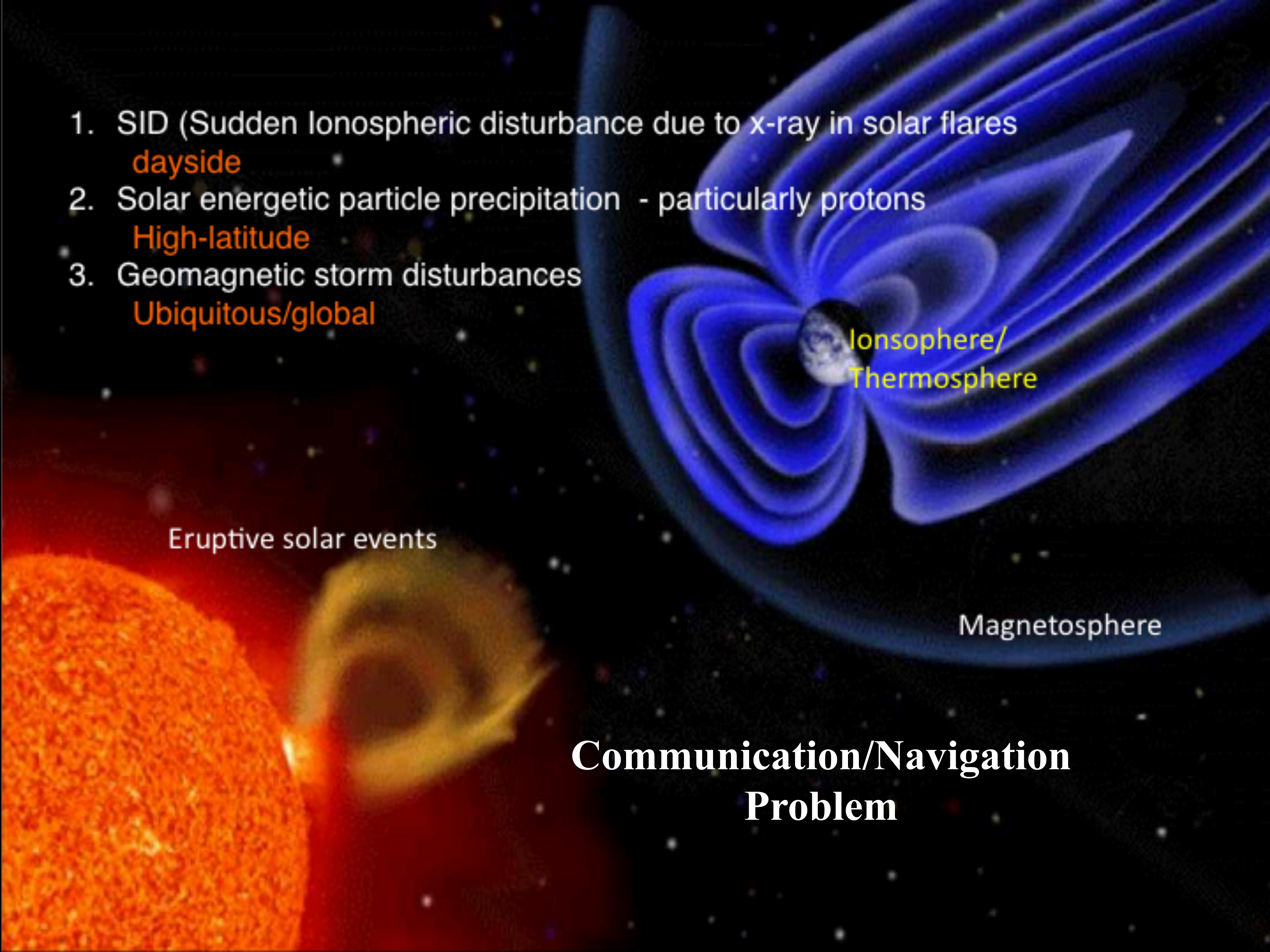
$$f_p \approx 9 \cdot 10^3 \sqrt{n_e}$$



Space Weather Effects in the Ionosphere

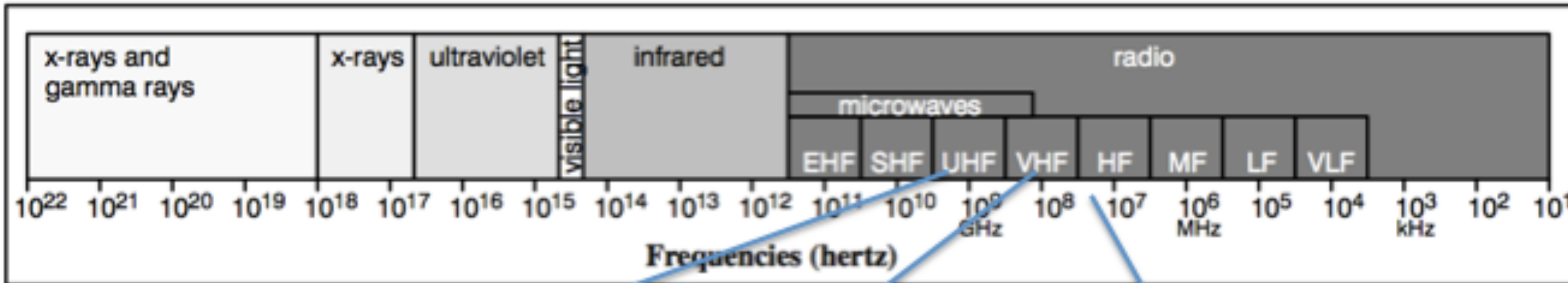
- Aurora – hemispheric power (satellite charging, scintillation)
- Satellite drag due to neutrals
- Equatorial bubbles/irregularities –scintillation, communication problems
- Radio blackout -- solar flare
- Polar Cap Absorption - solar energetic particles

1. SID (Sudden Ionospheric disturbance due to x-ray in solar flares
   dayside
2. Solar energetic particle precipitation - particularly protons
   High-latitude
3. Geomagnetic storm disturbances
   Ubiquitous/global



Communication/Navigation Problem

Types of space weather events affecting nav and commu



UHF – GPS

- Energetic protons/ particles – via SEEs - affecting GPS satellites components
- Geomagnetic storms/ ionospheric storm - cause scintillations

VHF:

- Energetic protons - PCA
- Geomagnetic storms
- Solar radio emission associated with flare/CME

HF:

- Solar flares/x-ray
- Energetic protons - PCA
- Geomagnetic activities

Solar radio bursts can directly affect GPS operation

Solar radio bursts during December 2006 were sufficiently intense to be measurable with GPS receivers. The strongest event occurred on 6 December 2006 and affected the operation of many GPS receivers. This event exceeded 1,000,000 solar flux unit and was about 10 times larger than any previously reported event. The strength of the event was especially *surprising* since the solar radio bursts occurred near solar minimum. The strongest periods of solar radio burst activity lasted a few minutes to a few tens of minutes and, in some cases, exhibited large intensity differences between L1 (1575.42 MHz) and L2 (1227.60 MHz). Civilian dual frequency GPS receivers were the most severely affected, and these events suggest that continuous, precise positioning services should account for solar radio bursts in their operational plans. This investigation raises the possibility of even more intense solar radio bursts during the next solar maximum that will significantly impact the operation of GPS receivers.

Cerruti et al., 2008, Space Weather

Sudden Ionospheric Disturbances – solar x-ray

- ✓ An SID can affect very low frequencies (e.g., OMEGA) as a sudden phase anomaly (SPA) or a sudden enhancement of signal (SES).At HF, and sometimes at VHF, an SID may appear as a short-wave fade (SWF).
- ✓ May last from minutes to hours, depending upon the magnitude and duration of the flare.
- ✓ Absorption is greatest at lower frequencies, which are the first to be affected and the last to recover. Higher frequencies are normally less affected and may still be usable.

Radio blackout events

Solar energetic particles

Radiation Storms

- HF/VHF degradation in polar region (a.k.a. Polar Cap Absorption)
- Energetic particles have detrimental effects on the onboard systems of GPS satellites (SEE impacts on spacecraft component)
- Energetic particle events can persist for a few days at a time

Geomagnetic Storms

Global impacts

- CME storms
- CIR storms

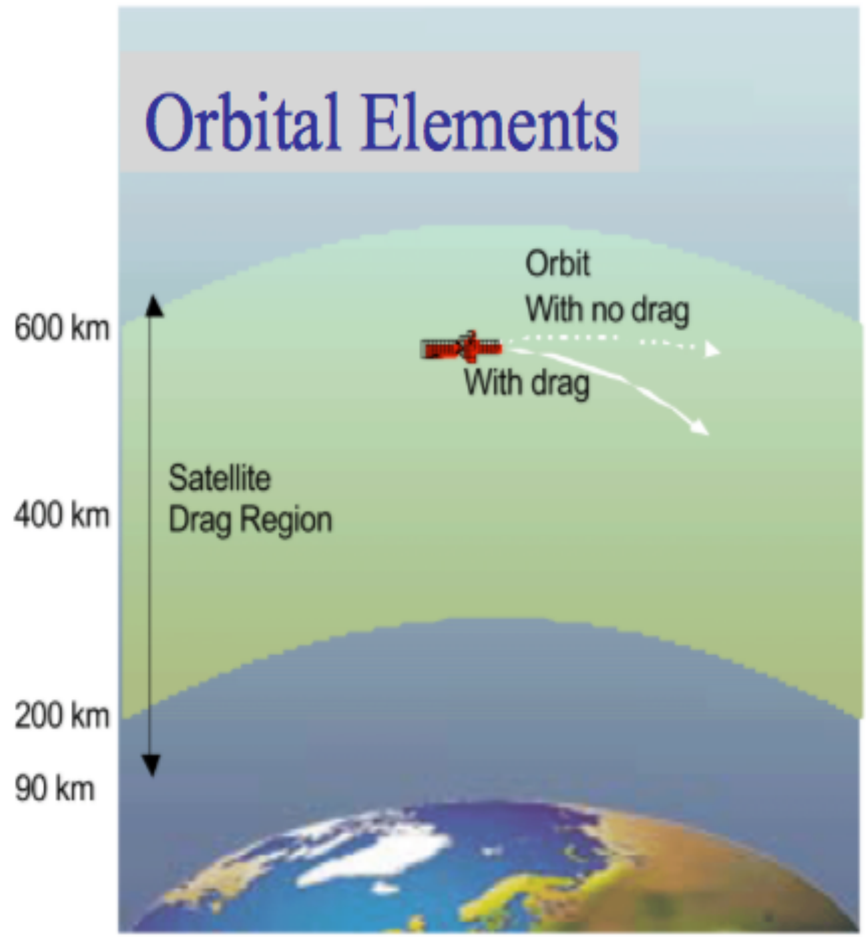
Affect HF radio communication – especially when the signal passing through the auroral zone or ionospheric irregularities

GPS - scintillation

Geomagnetic storms may last several days, and ionospheric effects may last a day or two longer.

Spacecraft Drag

- One of the major concerns for satellites in space is orbital decay.
- Orbital decay can be caused by mechanical, gravitational and electromagnetic effects.
- Spacecraft in LEO experience periods of increased atmospheric drag that causes them to slow, lose altitude and finally reenter the atmosphere.
- Short-term drag effects are generally felt by spacecraft <1,000 km altitude.
- Drag increase is well correlated with solar Ultraviolet (UV) output and additional atmospheric heating that occurs during geomagnetic storms.



Satellite Drag

- Atmospheric drag magnitude: $a_{drag} = \frac{1}{2}\beta\rho v^2$

  $\beta = \frac{c_D A}{m}$ is ballistic coefficient, ρ is atmospheric density and

  $v \cong v_{\text{sat}}$ is the spacecraft velocity

- Solar cycle and space weather have strong impact on neutral atmospheric density
- Increasing atmospheric drag impacts:

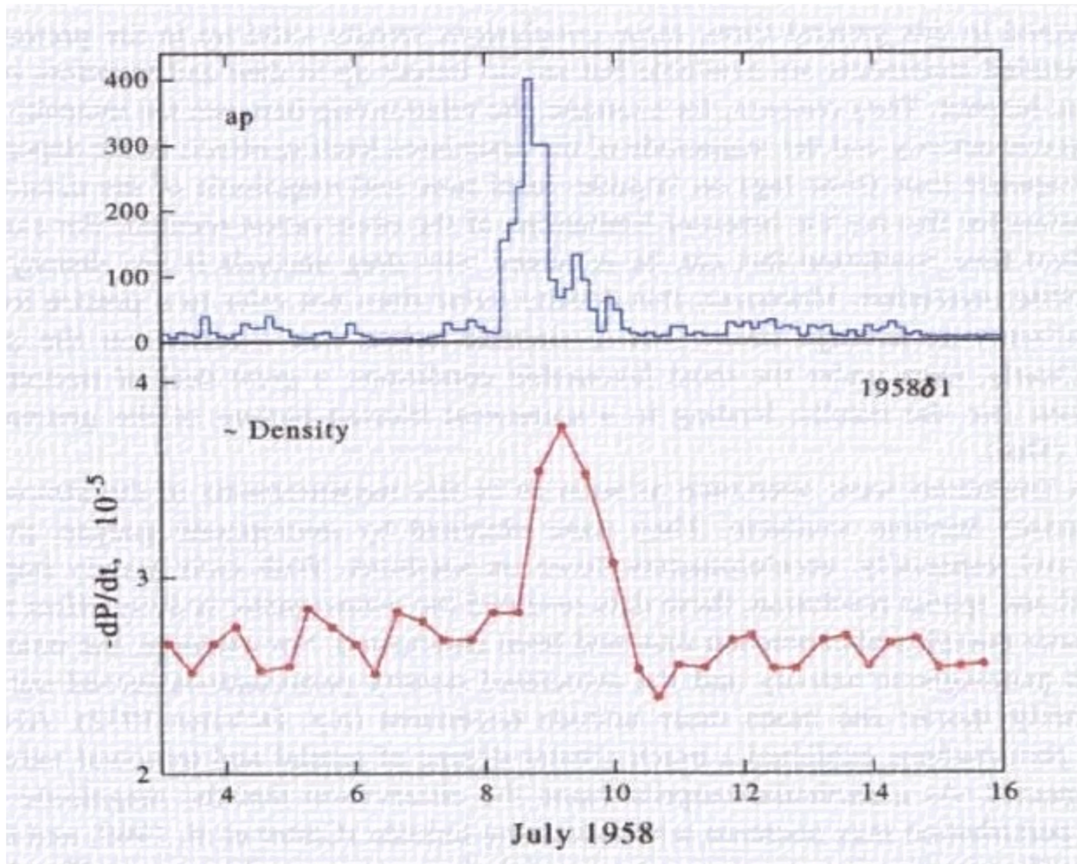
  Frequency of "Drag Make-Up" maneuvers for satellite to stay in control box
- Uncertainty in predicted atmospheric drag impacts:

  Future satellite position predictions

Neutral Density and Satellite Drag: 1^{st} observations

Extreme Geomagnetic Activity Indicated by Auroral Currents

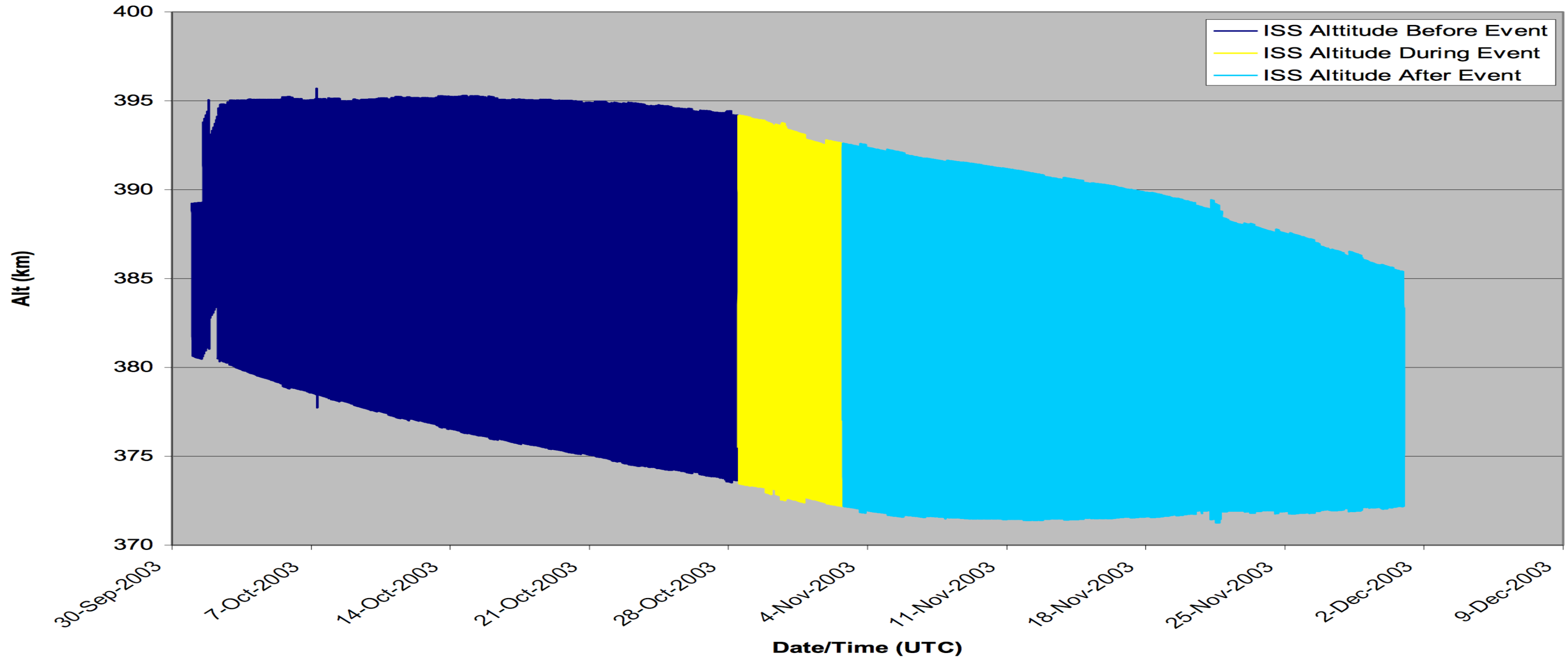
Rate of Orbital Period Change

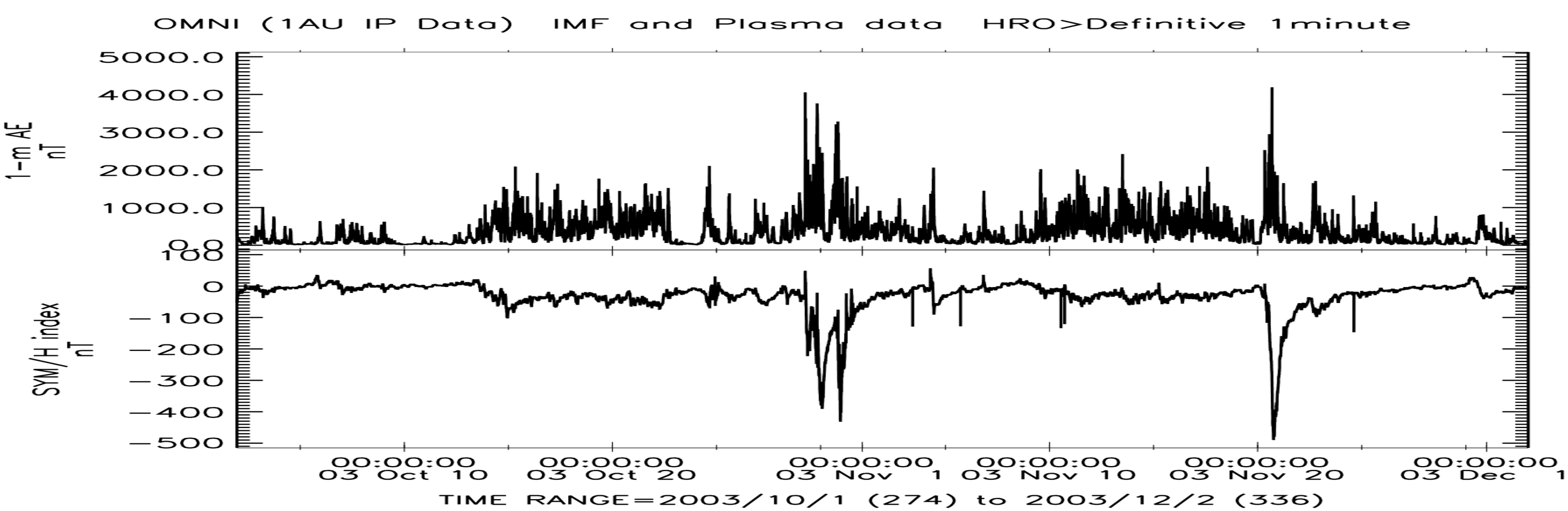


Sputnik Orbital Period Variation vs Day of July 1958

From Prolss (2011) after data from Jacchia 1959

ISS Altitude during Oct-Nov 2003





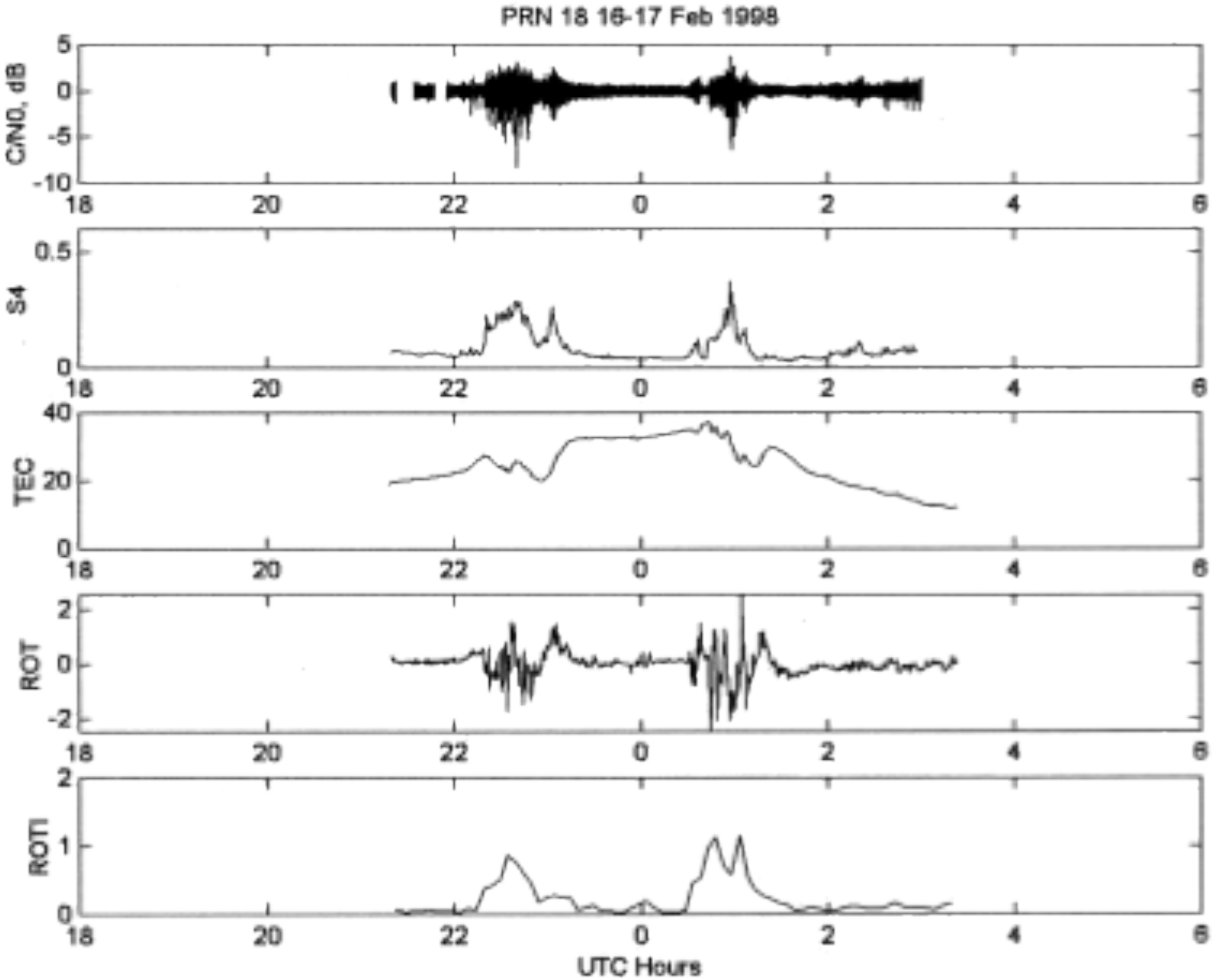
Ionospheric Irregularities/Scintillation

- Irregularly structured ionospheric regions can cause diffraction and scattering of trans-ionospheric radio signals. When received at an antenna, these signals present random temporal fluctuations in both amplitude and phase.

- Radio scintillation is the term used to represent the random fluctuations in signal phase and amplitude that develop when the radio waves propagate through ionospheric electron density irregularities. A measure of the degree of scintillation in the strength of a signal is the quantity S4 [Yeh and Liu, 1982], which describes the root-mean-square fluctuations in signal intensity, normalized by the average signal intensity:

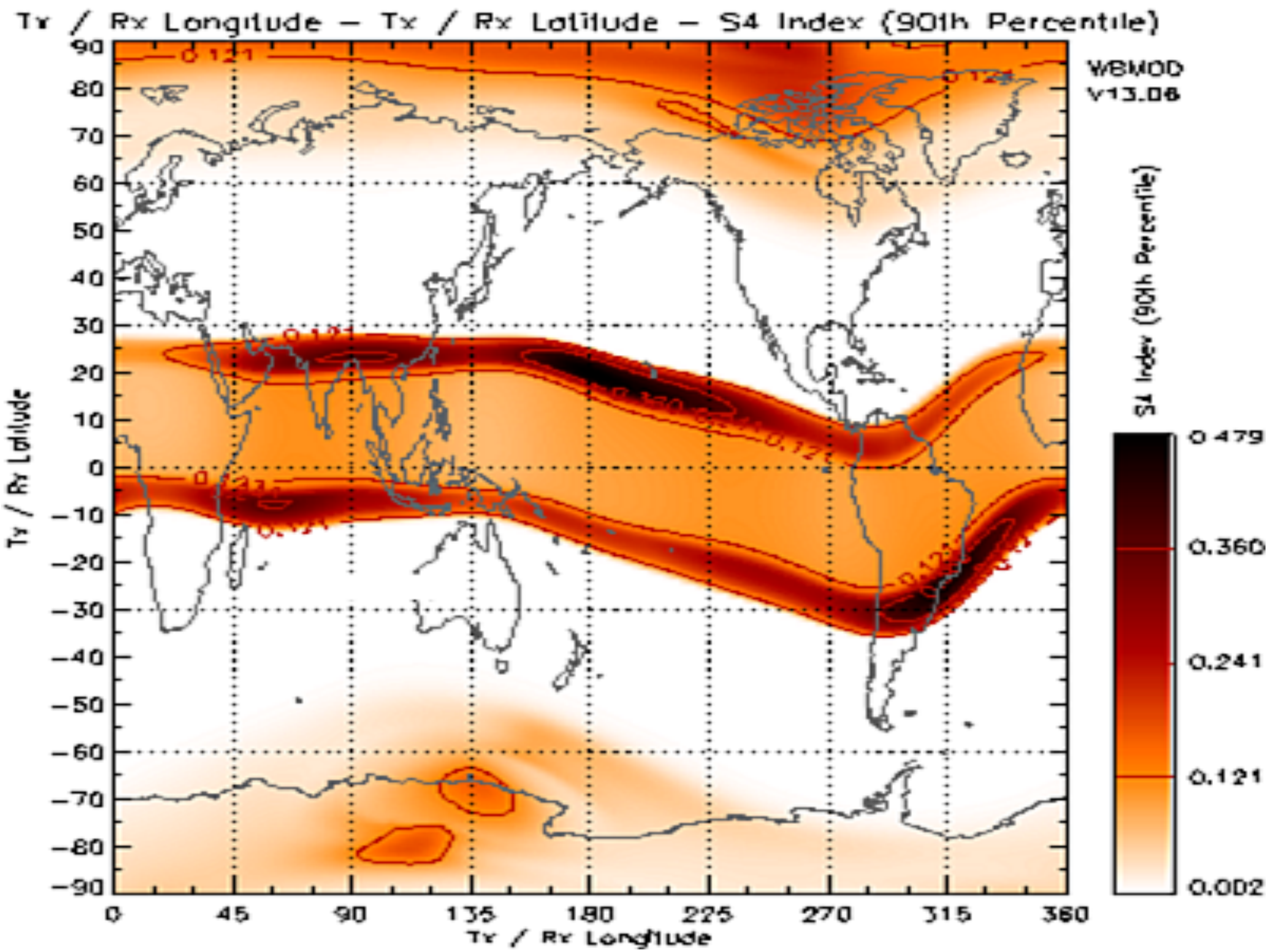
- Severe scintillation of the GPS satellite signals can result in loss of satellite tracking, which degrades GPS positioning accuracy. Even when satellite tracking is maintained, scintillation can cause errors decoding the GPS data messages, cycle slips, and ranging errors.

Scintillation



Basu et al., 1999

Global Scintillation Distribution



Ionospheric Scintillation Indices

$$S_4(f) = \sqrt{\frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2}} \propto f^{-1.5}$$

$$\sigma_\phi(f) = \sqrt{\langle \phi^2\rangle - \langle \phi\rangle^2} \propto f^{-1}$$

$$\mathrm{ROTI} = \sqrt{\langle \mathrm{ROT}^2\rangle - \langle \mathrm{ROT}\rangle^2}$$

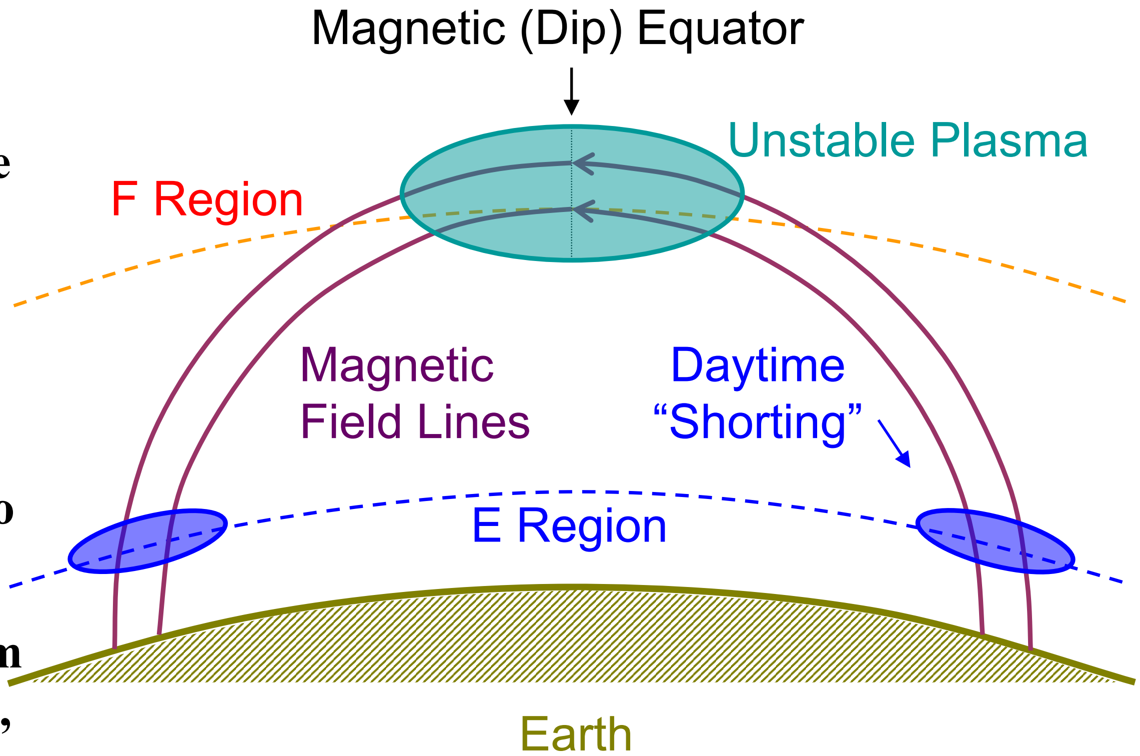
$$\mathrm{ROT} = C\frac{\Phi_I(t+\Delta t) - \Phi_I(t)}{\Delta t}$$

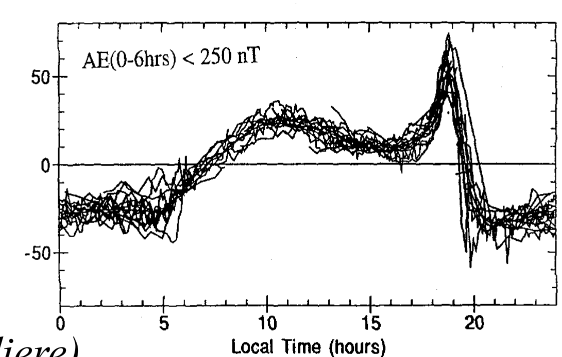
Courtesy: Pi at JPL

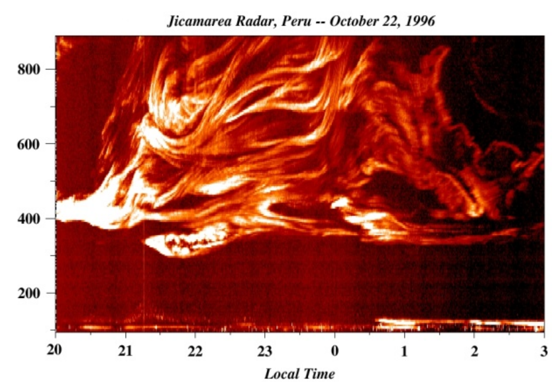
- **S_4 and σ_ϕ indices – amplitude and phase scintillation, respectively**
  - I – detrended signal intensity
  - ϕ – detrended signal phase
  - raw data is sampled at 20 or 10 ms (50 Hz or 100 Hz)
  - frequency dependent
  - Measurements of phase scintillation susceptible to local oscillator errors of transmitter and receiver
- **ROTI – Rate of TEC index**
  - ROT – detrended rate of TEC derived from dual-frequency phase data
  - ROT data sampled at 30 sec (or 1 s)
  - Not susceptible to local oscillator errors, in principle

Equatorial Plasma Bubbles

- Plasma moves easily along field lines
- Upward plasma drift supports plasma against gravity ⇒ unstable configuration
- E-region "shorts out" electrodynamic instability during day
- At night, E-region conductivity too small to short-out E field
- Instability in plasma grows to form equatorial plasma bubbles (EPBs), which contain irregularities seen by radars (right image) & which disrupt communications
- Irregularities mainly present during quiet times



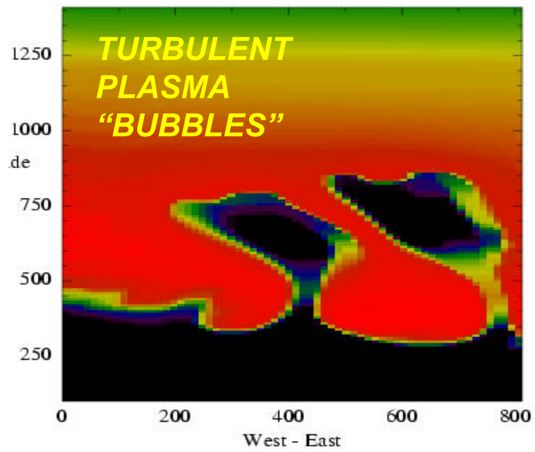




(Courtesy: de la beaujardiere)

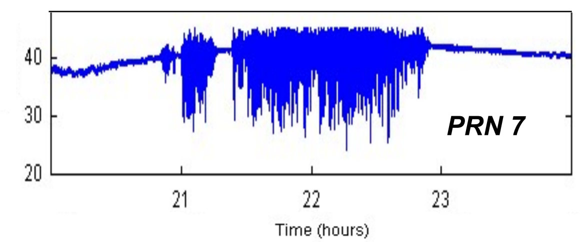
Plasma Bubbles

Plasma is subject to Raleigh-Taylor instability at night → formation of Equatorial Plasma Bubbles (EPBs)



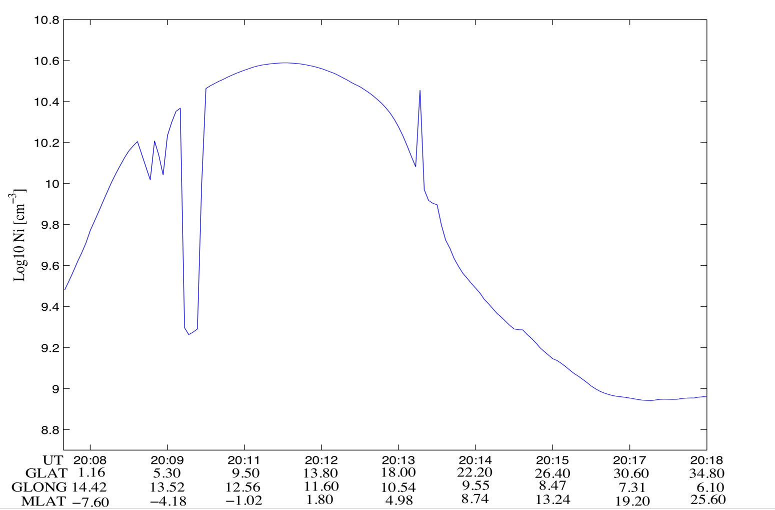
Courtesy: de la beaujardiere

Leads to highly variable reflection / refraction = “SCINTILLATION”



Scintillated GPS Signal

DMSP satellite Plasma density measurements



Ngwira et al., (JASTP, 2013)

Quick Quiz??

You have two spacecraft: (1) at 800 km altitude and (2) at 300 km altitude.

Which spacecraft is most impacted by satellite drag and why?